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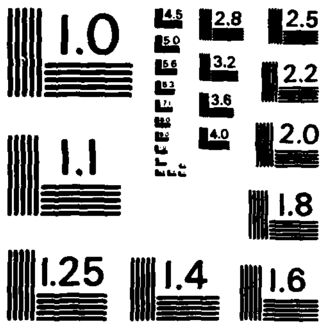

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This report summarizes the progress of research performed under AFOSR Contract Number F49620-82-K-0017, titled "Constraint-Based Scheduling in an Intelligent Logistics Support System: An Artificial Intelligence Approach". During the contract renewal period from March, 1984 to March, 1985, the continued development of a theory of hierarchical, opportunistic constraint-directed reasoning for job shop scheduling has been the focus of our research. Specifically, we have conducted work in the areas of opportunistic exploitation of constraints, and constraint-directed diagnosis. The former has led us to the use of multiple problem decompositions during schedule generation, while the latter has evolved toward development of a more broad based framework for reactive scheduling. An experimental software system called ISIS has continued its evolution and additional testing with simulated plant data has been performed. The design of a successor system called PHOENIX has been initiated.

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Annual Report

15 March 1984 - 14 March 1985

AFOSR Contract Number F49620-82-K-0017

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15 July 1985

Abstract

This report summarizes the progress of research performed under AFOSR Contract Number F49620-82-K-0017, titled "Constraint-Based Scheduling in an Intelligent Logistics Support System: An Artificial Intelligence Approach". During the contract renewal period from March, 1984 to March, 1985, the continued development of a theory of hierarchical, opportunistic constraint-directed reasoning for job shop scheduling has been the focus of our research. Specifically, we have conducted work in the areas of opportunistic exploitation of constraints, and constraint-directed diagnosis. The former has led us to the use of multiple problem decompositions during schedule generation, while the latter has evolved toward development of a more broad based framework for reactive scheduling. An experimental software system called ISIS has continued its evolution and additional testing with simulated plant data has been performed. The design of a successor system called PHOENIX has been initiated.

Table of Contents

Research Objectives and Status

1. Introduction

This report summarizes the progress of research performed under AFOSR Contract Number F49620-82-K-0017, titled "Constraint-Based Scheduling in an Intelligent Logistics Support System: An Artificial Intelligence Approach". A theory of hierarchical constraint-directed reasoning for the scheduling of job shops has been the focus of our research. An experimental software system called ISIS has continued in its development, and the design of a successor system called PHOENIX has been initiated. During the contract renewal period of march 1983 to march 1984, the following tasks were performed:

- A more opportunistic approach to schedule generation whereby attention is initially focused on bottleneck operations was explored. To this end, an Operations Research (OR) strategy for scheduling bottlenecks was implemented and coupled with the existing ISIS search strategy.

- A more general investigation into the use of a "resource-based" reasoning component as a means of better exploiting certain types of constraints was initiated.

- The evaluation scheme employed to estimate the quality of alternative schedules was revised to provide a better basis for constraint-directed diagnosis.

- A general "constraint checking" capability was designed and implemented for use both in the assessment of user made scheduling decisions, and in performing constraint-directed diagnosis.

- Constraint-directed diagnosis was placed within the larger arena of reactive scheduling and a general constraint-based framework for reacting to change was developed.

- A strategy for allocating aggregate resources (e.g. work areas) was designed and implemented, allowing the generation of schedules at different levels of precision.

- Experimental studies of the behavior of ISIS under the influence of various types of constraints were performed.

In this report, the goals of the renewal proposal are reviewed and progress toward these goals summarized. More detailed descriptions of various aspects of this work can be found in [Bourne&Fox 84, Fox&Smith 84a, Fox&Smith 84b].

2. Proposed Research Overview

We propose to continue research initiated under AFOSR Contract Number F49620-82-K-0017, titled "Constraint-Based Scheduling in an Intelligent Logistics Support System: An Artificial Intelligence Approach", toward the construction of an intelligent constraint-directed scheduling system. To date, our research as focussed on the development of a theory of hierarchical constraint-directed reasoning for the scheduling of job shops. An experimental software system called ISIS-II has been constructed and testing of the system on simulated plant data has yielded promising results. Our objective in continuing this research is to improve the functionality of ISIS-II and extend research by investigating the issues of:

- Refining the system's architecture to allow constraints to be exploited in a more opportunistic fashion during scheduling.
- Improving schedules through constraint-directed diagnosis of constraint satisfaction failures. This involves the identification of failures, the determination of cause, and the selection of corrective action.
- Conducting further experimentation with the system.

2.1. Opportunistic Reasoning

The original proposal stated:

> The integration of multiple levels of analysis has proved effective in improving the performance of ISIS-II. Tests comparing the hierarchical system to other, non-hierarchical versions have clearly indicated its superiority. However, while ISIS-II integrates multiple levels of analysis, the search conducted at any given level proceeds in a single direction through the schedule under development. As such, the constraints relevant to decisions in a particular region of the space are considered only when the search enters that region. We have identified situations where a prior recognition of the most important and most certain constraints at a given level could lead to a more efficient trajectory through the search space.
>
> Our research will investigate the use of more opportunistic forms of search control within the existing ISIS-II hierarchical framework. In particular, we propose to augment the pre-search analysis currently performed at each level to identify multiple "islands of certainty" from which to expand the search.

Our investigation into more opportunistic forms of search has resulted in an important realization that has led us in a somewhat different (but more appropriate) direction than was anticipated in the proposal. While it was originally felt that useful "islands of certainty" could be established during the pre-analysis phase of each level of the search, it has since become apparent that the local and incomplete view of the problem that the system is operating with during the search for a given order's schedule does not provide a sufficient basis for such decision making. The determination of where to go about establishing islands in the developing schedule must proceed under the direction of a more global (or strategic) decision making process, and, moreover, the establishment of islands may itself constitute a significant portion of the overall scheduling task. Accordingly, our focus has turned to developing a framework wherein global recognition of the most important constraints guides the formation of appropriate initial subtasks. The solutions to these subtasks then serve as islands (or fixed points) in the developing schedule and further subtasks can be identified, etc. This approach has pointed up the need for an ability to decompose and reason about the scheduling problem in different ways. For example, it is sometimes more appropriate to focus on scheduling a resource (i.e. adopt a resource-based perspective) than it is to focus on scheduling an order (the perspective adopted by ISIS-II). Our work has sought to

- establish a basis for deciding how to best partition the problem solving effort between the scheduling perspectives afforded by resource-based and order-based problem decompositions, and

- investigate resource-based reasoning strategies, and their integration with the order-based reasoning strategy of ISIS-II, as a means of generating schedules in a more opportunistic fashion.

This section briefly summarizes the results we have obtained thus far.

The use of multiple decompositions of the scheduling problem was motivated by an examination of the primary source of complexity in scheduling, the conflicting nature of the domain's constraints. In the final analysis, the quality of a schedule will depend upon the extent to which various kinds of conflicts have been optimally resolved. Yet the ability to optimally resolve a given conflict necessarily requires that all constraints involved in the conflict be isolated within a common subtask. Herein lies the problem with adopting a single problem decomposition. A given decomposition brings specific types of constraints to the foreground and deemphasizes others. Hence, it promotes the resolution of specific types of conflicts at the expense of others. For example, the ISIS-II search architecture, which adopts an "order-based" decomposition, emphasizes the constraints that surround each particular order (e.g. precedences, due date, etc.), and constraints that cut across several orders (e.g. sequencing preferences at a particular resource) cannot be effectively addressed. Our conclusion is that the range of conflicts to which the system can attend can be broadened by employing multiple problem decompositions. In particular, the inclusion of a resource-based reasoning component is necessary to effectively exploit the constraints that lead to efficient utilization of resources. The key to integrating this reasoning component with the order-based strategy of ISIS-II is to identify the subtasks within each decomposition (resource-based and order-based) that isolate the essential conflicts.

To test out this theory we have configured a scheduling system that possesses both resource-based and order-based reasoning components. Specifically we have

- implemented an Operations Research (OR) strategy for scheduling particular resources to serve as the system's resource-based reasoning component.

- generalized the ISIS-II architecture to operate on arbitrary portions of the operations graph of a given order. This results in an order-based reasoning component that is capable of treating the previously established reservations as islands from which to expand in completing the schedule of a given order.

Using these components, we have explored the use of a rather well known heuristic as a basis for partitioning the scheduling effort, namely that the essential resource-based conflicts center around the allocation of bottleneck resources. Making the assumption that the allocation decisions at the bottlenecks are indeed the most critical decisions to be made, we have experimented with a strategy whereby the OR scheduling strategy is invoked initially to establish reservations on the bottleneck resource(s), with the revised ISIS-II strategy then employed to complete the schedules for each individual order. The results, though preliminary, clearly illustrate the advantage of adopting an additional scheduling perspective (see Section 2.3).

Bolstered by the above "proof of principle" experiments, work has been initiated on the design of a successor system to ISIS, called PHOENIX. The objectives are to

- investigate more general, constraint-directed approaches to resource-based reasoning, analogous in scope to the ISIS order-based approach.

- look more generally at strategies for utilizing multiple problem solving perspectives, both in schedule generation and in reactively repairing schedules in response to unexpected events (see Section 2.2).

This work will be carried out during the current renewal period.

2.2. Constraint-Directed Diagnosis

The original proposal stated:

> One problem frequently encountered by hierarchical search systems is a poor ability to recognize problem areas in the search space, and relate them to specific decisions previously made at higher levels (Fahlman, 1973). This problem arises within ISIS-II as well. Constraints do not exist independently of one another. But rather a commitment to a particular value for one constraint may quite likely affect the possible choices of others and, thereby, reduce or increase the degree to which they can be satisfied. Budget constraints affect the number of shifts to be used in the production process. A selection of shifts, in turn, constrains how well due dates will be met. To reduce the complexity of its search, ISIS-II must make commitments with respect to specific types of constraints at each level of analysis. Given such interactions amongst constraints, there is no guarantee that these commitments will not later lead to unacceptable constraint satisfaction failures

at lower levels.

There are three issues that must be addressed in providing an ability to react to such situations. The first issue concerns the recognition of search failures. Given that any solution produced is likely to require relaxation of at least some of the constraints, the problem here is one of determining whether or not constraints have been satisfied to an acceptable degree. To this end, we propose to investigate alternative criteria for assessing the quality of the results produced at each level of the search.

The second issue that must be addressed is that of determining the cause of the a constraint satisfaction failure. In this case, knowledge of the interactions amongst constraints can provide the necessary means. Our previous work on constraint representation has made much progress toward the formalization of constraint interaction knowledge.

The third issue that must be addressed is how to redirect problem solving in order to rectify these constraint failures. An altered search, i.e., additional operators used, may be performed at the level in which the constraint failure occurred, or search may be re-performed at another level which was determined to indirectly cause the constraint failure. We propose to explore reasoning strategies that exploit this knowledge to refocus the system's attention on prior commitments that need to be reassessed.

Our work on recognition of search failures has focused on the suitability of the ISIS constraint evaluation scheme as a basis for diagnosing constraint *satisfaction failures*. Briefly, this is the process whereby the constraints relevant to a particular hypothesis (representing a specific set of scheduling decisions) are collected and applied to yield a measure of worth (intuitively meant to reflect how well this hypothesis satisfies the constraints). Decisions as to which hypotheses to extend at each step of the search are made on the basis of these rating. The rating assigned to the hypothesis chosen as the final result of the search should thus provide the basis for diagnosing constraint satisfaction failures.

Unfortunately, the specification and interpretation of constraint utilities within ISIS (and hence the composite rating derived from the set of utilities assigned) was found to diverge from the intuitive notion of "degree of satisfaction" that is required for diagnosis. Utility values and composite hypothesis ratings are defined to range from 0 to 2 with an interpretation of 0 - inadmissible, 1 - indifference, and 2 - maximal support, which implements a more ad hoc measure of worth. In practice, this leads to the assignment of utilities that mix two different notions:

1. the degree to which the constraint has been satisfied (if the utility assigned is viewed in relationship to the utility that would be assigned to other alternatives)
2. the importance of the constraint (if the utility assigned is viewed in relationship to the other constraints influencing the decision under consideration)[1]

[1] The ISIS constraint representation does, in fact, define importance as a separate concern. This adds to the confusion.

To provide a basis for recognition of search failures, a new evaluation scheme was designed and implemented. Utility was replaced by the more precise measure of degree-of-satisfaction, which ranges from 0 (unsatisfied) to 1 (satisfied). Points within this range indicate various degrees of partial satisfaction. The importance of satisfying the constraint was thus clearly isolated as a separate concern.

Using the new evaluation scheme, a general "constraint checking" facility was designed and implemented. This provides a mechanism for recognizing constraint satisfaction failures, which is defined to be a function of the importance and degree of satisfaction of the relevant constraints. It also provides a means for assessing the quality of scheduling decisions made by the human scheduler, in which case it provides commentary as to how well constraints have been satisfied, and the likely consequences of the decision.

We have been unable, thus far, to investigate alternative strategies for reacting to detected constraint satisfaction failures (the third issue identified in the proposal above). Our work, to date, has been focused on developing a general framework for organizing such system behavior. This framework, which views reaction to search failures as a special case of the more general problem of reacting to change, is described in [Fox&Smith 84b]. The results of our work in opportunistic reasoning have also sharpened our understanding as to how the search might be redirected in the face of constraint satisfaction failures. The use of multiple decompositions suggests a natural mapping of constraint types to subtasks that can be exploited once the constraint causing the failure has been identified. Work is proceeding in this area during the current renewal period within the context of the PHOENIX system.

2.3. System Evaluation

The original proposal stated:

> As stated in the original proposal, a major goal of our research is to construct a system with good functionality. This goal is reiterated here for emphasis, as evaluation of system performance remains a fundamental concern. We intend to further analyze the system across two dimensions.
>
> The first dimension of analysis will address the interactions amongst constraints. Initial experiments will be performed in an effort to refine the constraint interaction knowledge required for constraint-directed diagnosis. Next, an analysis will be performed to assess the performance gains afforded by this diagnostic capability.
>
> The second dimension of analysis will focus on the performance tradeoffs involved in augmenting the system with the ability to search in a more opportunistic fashion. Comparative studies of the competing search architectures will be performed.

With respect to the first dimension of analysis, series of experiments were performed in both flow shop and job shop scheduling environments. These experiments allowed us to isolate the effects of various types of constraints on the schedules produced, and assess the quality of the constraint knowledge in the system. These experiments pointed up specific deficiencies which resulted in a reformulation of some constraint knowledge, and also highlighted the limitations of working with a single decomposition of the scheduling problem (which led to the system configuration summarized in Section 2.1). Since the constraint-directed diagnosis facility has not yet been fully implemented, no comparative analysis of performance gains along these lines has been done.

A comparative analysis of the opportunistic system architecture summarized in Section 2.1 and the ISIS architecture detailed in [Fox&Smith 84a] was also performed. The opportunistic architecture was found to produce schedules that exhibited considerably less work-in-process time than those generated by the basic ISIS strategy, particularly in situations where there was a high degree of contention for resources. We are currently implementing a commonly accepted dispatch rule approach to provide an additional point of comparison with the new architecture.

3. New Areas of Research

This section describes a new area of research which was not identified in the original proposal, but has played an important role in our research.

3.1. Allocation of Aggregate Resources

In earlier versions of ISIS, two simplifying assumptions were made with respect to the allocation of resources to manufacturing operations:

- the resources to be allocated were always considered to be individual units (e.g. machines) that could be assigned to only one operation at any given point in time, and
- an operation could not be split over more than one resource.

These assumptions stem from a overall system orientation toward the generation of detailed schedules for production and a consequential methodological commitment to reason about resources only at the most detailed level of precision. However, our experience in real factory environments has shown that it is often more appropriate to reason about some resources at an aggregate level (even if the target is a detailed production schedule). For example, in scheduling grinding and polishing operations, the resource to be allocated might be the grinding room, a work area consisting of some number of individual grinding stations. It is not really important that a specific grinding station be employed for a given operation (as it might be in the case of machine assignments). What is important is that there exists enough capacity in the grinding room to handle the operation. Moreover, it is probably unlikely that all pieces in the order will be processed at the same station. The order will probably be split across several stations to expedite its processing.

Recognizing the inflexibility of focusing solely on the allocation of individual resources, we have augmented the system with an ability to reason about resource allocation at different levels of abstraction. Principal elements of the technique devised include

- a hierarchical framework for representing resources wherein individual resources are grouped into enclosing work areas and higher level characterizations of available capacity are introduced at aggregate levels. This allows aggregate resource allocation decisions to be based strictly on required capacity, and permits the simultaneous allocation of such resources to more than one operation at a time.

- a rule based specification of heuristics for determining required capacity at aggregate levels. This allows, for example, the association of specific order splitting strategies with particular work areas in the plant.

At present, the use this aggregate resource allocation scheme is limited to those areas of a manufacturing plant that are comprised of non-machine work stations (e.g. grinding stations, packing stations, etc.), and the system remains focused toward generating a schedule at a pre-specified level of detail. However, with appropriate generalization we foresee a much broader application of this technique in the development of schedules at different levels of abstraction according to varying user needs (e.g. long range planning vs short term scheduling). Our current work is exploring this possibility.

4. Conclusions

In reviewing the above information, we have found that many but not all of the objectives set forth in the proposal have been achieved. We believe that substantial progress has been made in furthering the research that was initiated during the original contract period toward the development of a theory of hierarchical, constraint-directed reasoning for job shop scheduling. In particular, our work in the area of opportunistic construction of schedules has given us valuable insights with respect to constraint-directed search architectures. With the development of the PHOENIX system during the current renewal contract, we are optimistic that these insights, and the other work we have done, will lead to substantial improvements in both the quality of the schedules generated and the robustness of the overall system.

5. Publications

[Bourne&Fox 84] Bourne, D.A., and M.S. Fox.
Autonomous Manufacturing: Automating the Job Shop.
Computer 17(9), September, 1984.

[Fox&Smith 84a] Fox, M.S., and S.F. Smith.
ISIS: A Knowledge-Based System for Factory Scheduling.
Expert Systems 1(1), July, 1984.

[Fox&Smith 84b] Fox, M.S. and S.F. Smith.
The Role of Intelligent Reactive Processing in Production Management.
In *Proceedings 13th Annual CAMI Technical Conference.* Clearwater, Florida, November, 1984.

6. Research Staff

- Fox, Mark S.
- Ow, Peng Si
- Smith, Stephen F.

7. Related Presentations: March 1984 - March 1985

"Artificial Intelligence in Manufacturing", invited seminar, Dept. of Mechanical Engineering, Massachusetts Institute of Technology, March 15, 1984.

"A Constraint-Directed Reasoning Approach to Job-Shop Scheduling", APICS, Charlotte, NC, March 20, 1984.

"Artificial Intelligence in Manufacturing", Canadian Institute for Advanced Research Symposium on AI, Ottawa, Canada, March 27, 1984.

"A Constraint-Directed Reasoning Approach to Job-Shop Scheduling", Carleton University, Ottawa, Canada, March 18, 1984.

"A Constraint-Directed Reasoning Approach to Job-Shop Scheduling", Wharton Business School, University of Pennsylvania, Philadelphia, PA, April 4, 1984.

"Artificial Intelligence in Manufacturing", Industrial Engineering Dept, Purdue University, West Lafayette, IN, April 24, 1984.

"Artificial Intelligence in Manufacturing", Business School, University of Michigan, Ann Arbor, MI, April 25, 1984.

"Artificial Intelligence in Manufacturing", Technology Transfer Society, Los Angeles, CA, May 18, 1984.

"A Constraint-Directed Reasoning Approach to Job-Shop Scheduling", Westinghouse R&D Lab., Pittsburgh, PA, May 22, 1984.

"Knowledge Representation for Decision Support", IFIP WG 8.3 Working Conference, Durham, England, July, 1984.

"Artificial Intelligence in Manufacturing", Texas Instruments, Inc., Dallas, TX, August 21, 1984.

"Artificial Intelligence in Manufacturing", Rockwell International, Downey, CA, August 22, 1984.

"Artificial Intelligence in Manufacturing", Boeing Conference, Computer Science in Aerospace, Seattle, WA, September 11, 1984.

"Intelligent Management Systems", CAMI Factory Management Meeting, Pittsburgh, PA, September 26, 1984.

"ISIS - A Knowledge-Based Approach to Factory Scheduling", CAMI Factory Management Meeting, Pittsburgh, PA, September 27, 1984.

"Artificial Intelligence in Manufacturing", Association for Computing Machinery 1984 Conference, San Francisco, CA, October 8, 1984.

"Artificial Intelligence in Manufacturing", Research Planning Workshop for Applications of Artificial Intelligence in Manufacturing, Dayton, Ohio, November 8, 1984.

"Constraint-Directed Reasoning in Job-Shop Scheduling", invited talk, SIGART Chapter Luncheon, Dayton, Ohio, November 9, 1984.

"The Role of Intelligent Reactive Processing in Production Management", invited talk, 13th Annual CAMI Technical Conference, Clearwater, Florida, November 14, 1984.

"Reasoning with Constraints", invited talk, University of Utah, Salt Lake City, UT, December 5, 1984.

"Artificial Intelligence in Manufacturing", tutorial, "Case Study of Artificial Intelligence in Job Shop Scheduling, Tutorial, CPMS Seminar on Expert Systems, William Penn Hotel, Pittsburgh, PA, December 11, 1984.

"Artificial Intelligence and Its Role in Manufacturing's Future", Institute of Industrial Engineers Conference, Pheonix, AZ, February, 11, 1985.

"A Re-visit to ISIS", "Uses of SRL in System Development and Verification", CAM-I Conference, Orlando, FL, February, 21, 1985.

"Artificial Intelligence in Manufacturing", invited talk, General Electric R&D Labs, Schenectady, NY, March 11, 1985

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